LONGITUDINAL BEAM MOTION IN THE FERMILAB BOOSTER ACCELERATOR

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Summary

The intensity of the Fermilab booster accelerator has been limited in part by longitudinal effects. These include longitudinal space charge blowup prior to RF capture, phase space dilution during capture and insufficient voltage to provide bucket area to accelerate the diluted beam. Measurements of beam properties under these conditions, as well as high intensity effects during acceleration, are presented.

Longitudinal Emittance

Longitudinal effects of space charge forces on a drifting bunched beam, and the various means by which these effects can be modified have been investigated by a number of authors. The results of these investigations have been applied to the Fermilab injector system, and momentum spread measurements have been made near the last linac tank, prior to capture, and after capture.[1,2]

The momentum distribution for an 80-mA beam, as measured at the beginning of the 200-MeV injection line, without emittance corrections, is shown in Figure 1 (solid curve). This spectrum is somewhat narrower than the design goal, and is the result of adjusting the phase of the last linac tank.[3] This does not, however, represent the momentum spectrum at capture time in the booster. The injected momentum spread has been determined by powering the booster at a fixed field and analyzing the frequency spectrum of the coasting beam (Schottky scan). Since there is a beam loss during the measurement interval, the results should be interpreted as a lower limit for the momentum width. The second curve (Δ) in Figure 1 is the momentum spectrum (debuncher off) of the circulating beam. The width is 0.23% for 95% of the beam. This result led to the installation of a debuncher.[4] The third curve (0), Figure 1, is the momentum spectrum obtained after the installation of the debuncher. The spectrum width for 95% of the beam is now 0.15% and provides more favorable conditions for acceleration. Once the permanent debuncher power system is operational, the linac will be retuned to give a longer bunch length at the debuncher. This will allow a further reduction in the momentum spread at capture.

RF Capture

The theoretical aspects of adiabatic capture have been understood for some time. Most of these discussions have been limited to cases where the voltage

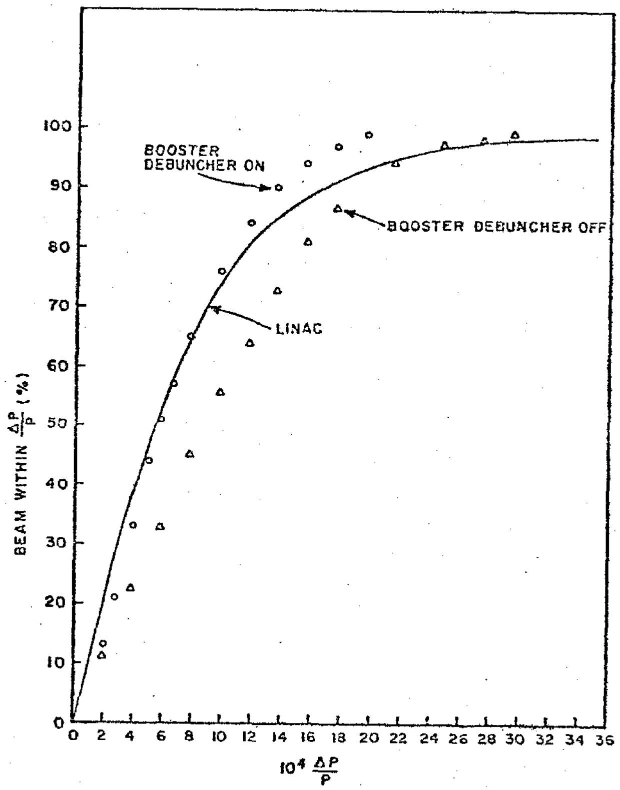

Figure 1. Momentum distribution of an 80-mA linac beam.

program was a smoothly varying function of time and the magnet field was static. Neither of these conditions is present in the booster.

The 16 rf cavities were to be turned on sequentially at 10-μsec intervals to a total voltage of 100 kV/turn, which would yield a stationary bucket area of 2.27 eV-sec. If the momentum spread of the injected beam were ±0.08%, its phase space area would be 1.63 eV-sec and the buckets would be 72% filled, provided the capture were adiabatic. By using the proper difference equations and actual voltage turn-on, it has been shown that dilution of the beam phase space area will always occur even in the absence of acceleration.[5]

Other numerical calculations which included the effects of acceleration during the trapping process, showed larger dilution of the beam phase space area.[6,7] For instance, it was found that in order to realize 100% capture (full bucket) of a beam whose momentum spread was ±0.13%, the final voltage should be 280 kV/turn. This voltage is a factor of two larger than would be expected for an adiabatic capture process.

At the present time, the cavities are turned on to a total voltage of 250 kV/turn in about 160 μsec. Capture efficiency has been measured versus linac beam current with debuncher on and off. The measurements

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which were conducted with a single-turn beam, demonstrated that the capture efficiency depends upon the linac beam current, via the momentum spread. At best, 95% of the beam could be captured.

As the number of injected turns is increased, the capture efficiency is reduced. This is, in part, due to a time variation of the central momentum caused by a transient phase shift between linac and debuncher.[4]

Acceleration and Bucket Area

A calibrated rf voltage monitor system has been installed in the booster. Synchrotron frequency measurements and accelerating threshold measurements were made to check the calibration throughout the cycle. A typical bucket area curve derived from the voltage measurement is shown in Figure 2. There is beam loss associated with the small bucket area in the neighborhood of 3 msec in the cycle. The decreased bucket area is the result of lowered voltages caused by unanticipated power losses in the ferrite tuners.

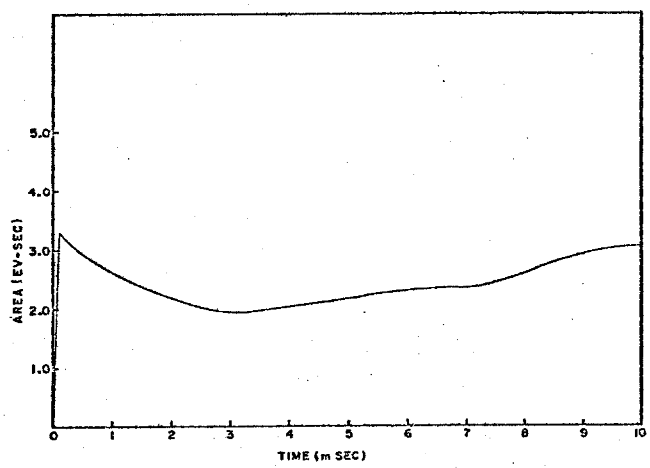

Figure 2. Bucket area during the first 10 msec.

Two modified rf cavities, which are tunable for the first 5 msec of the booster cycle, were installed in order to increase the available bucket area early in the cycle. With the two additional cavities and the debuncher operating, beam losses, for a single-turn beam of 80 mA from the linac, were reduced to about 5-10% at capture (losses before 0.5 msec) and about 5% from just after the capture loss until the two special cavities were shut off. These losses are quoted for currents of about 80 mA from the linac with the debuncher operating.

The phase space density of the beam after capture was investigated by introducing a known restriction in the accelerating bucket area and measuring the resulting beam transmission. The results are shown in Figure 3. A comparison of the phase space distribution after capture with the momentum distribution of the debunched beam before capture indicates a dilution of at least 50% during the capture of an 80 mA beam.

High Intensity Effects

Because of the figure of quality of the rf cavities used in the booster, it was anticipated at the design stage that beam loading at high intensity could induce an appreciable cavity voltage. The rf system has feedback loops (two at high level and two at low level) which control the cavity voltage, cavity tuning, beam-cavity phase, and beam radius throughout the cycle. The criteria for successful operation of these loops are: (1) damped phase oscillations, (2) stable beam radius, and (3) constant cavity voltage as the intensity varies. At the present operating intensity, these criteria are satisfied.

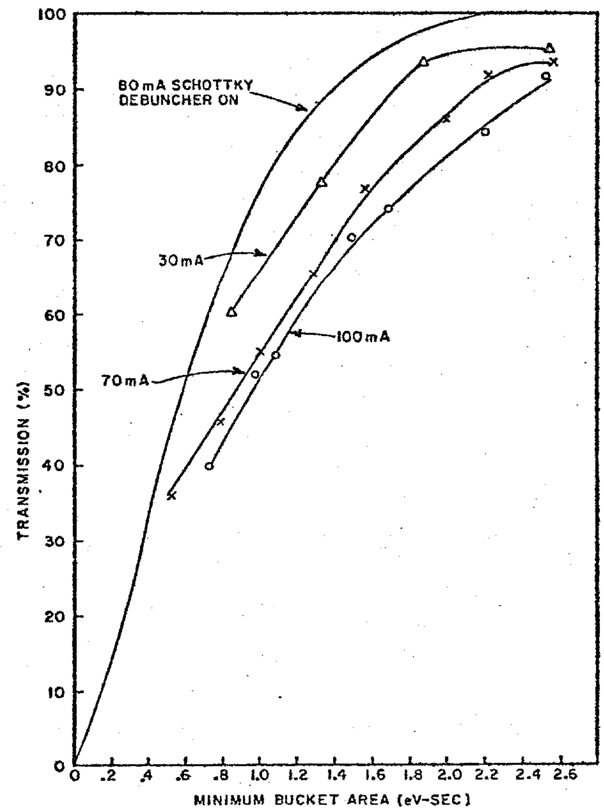

Figure 3. Transmission versus bucket area.

The booster, being a fast-cycling synchrotron, has no vacuum chamber to shield the beam from the magnets. Consequently, in the vicinity of transition, where the beam is tightly bunched, a considerable amount of energy can be lost to the magnet laminations.[8] At the design intensity of 3.8×10^{12}, the predicted loss is 50-100 keV/turn/particle.

Recent measurements at 30% of the design intensity indicate an anomalous energy loss of 30 keV/turn. This loss shows up as a shift in the synchronous phase angle near transition as the intensity is increased. This phase shift is not the result of beam loading since there is no measurable decrease in the peak rf voltage as the intensity is raised.

No coherent phase oscillations attributable to beam instabilities have been observed.

References

1. S. Ohnuma, "Do We Need a Debuncher in the 200-MeV Transport System?," Fermilab Internal Report, TM 319, July 1971.